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Soil nailing optimisation: lost opportunities in current practice

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ABSTRACT: This paper analyses 127 cases histories in the US and Europe to evaluate the current state of soil nailing practice with respect to soil nail lengths and density, wall heights, wall inclination, and shotcrete thickness, as well as applications. When the cases are considered by project size and soil type, certain inefficiencies appear. Namely, smaller projects exhibit conservatism in nail density and shotcrete thickness, and use only a fully vertical wall. In contrast on larger projects, there appears to be an optimization of these factors. What appears to occurring is that for smaller projects and/or shorter walls, contractors are adopting conservative rules of practice instead of actually designing the projects in accordance with published design manuals. A single, small case is reconsidered using the Geotechnical Engineering Circular No.7, GEC7 design guide resulting in an estimated 7.2% savings.

KEY WORDS: Soil Nailing, Codes, Design, Optimisation.

1 INTRODUCTION

Soil nailing is primarily used to stabilise slopes and excavation faces. The technique comprises of the installation of reinforcing 'nails', sub-horizontally, into a soil mass, which improves soil coherency. The method originated from rock bolting and multi-anchorage systems [1,2,3]. Methods vary with soil type but generally consist of the following [4]:
1) Initial excavation of 1-2 m deep; can remain unsupported for typically 24-48 hrs.
2) Nail installations (driving or placement into a pre-drilled, grouted borehole).
3) Facing construction (to support open-cut before the next lift of soil is excavated).

Europe's first documented soil nail wall was constructed in Versailles in 1972 and grew in popularity over the next two decades, culminating in Clouterre [1], a comprehensive document detailing construction methods. This paper explores inconsistencies since this publication and provides insight into cost savings measures.

2 BACKGROUND

The first major research program on soil nailing (Bodenvernagelung) was undertaken in Germany 1975-81 [3]. Prior, Mason filed a US patent in 1970, having constructed several projects using the technique [3]. The French national research program Clouterre [1] in 1991 was the first comprehensive document, which detailed construction, design codes, and analysis on full-scale models.

The FHWA Manual for design and construction monitoring of soil nail walls [3] was finalized in October 1998 and was an outcome of Demonstration Project 103 (DP103), which commenced in 1992 as an American equivalent to Clouterre [1]. DP103 aimed at introducing soil nailing to American State Departments of Transportation. The focus was for permanent installations. In 2003, Geotechnical Engineering Circular No.7 Soil Nail Walls (GEC7) [4] was published, which essentially up-dated DP103 [4]. Following the UK's Construction Industry Research and Information Association's (CIRIA) ground engineering Research Project 674, a best practice guidance [2] was published in 2005. In 2008, the Hong Kong government's Civil Engineering Department published Geoguide 7: guide to soil nail design and construction [5].

2.1 Design manuals, standards and guidelines

In the US, GEC7 is used in the public sector [6] with additional widespread private sector usage. Some European countries developed their own soil nailing standards, such as Clouterre [1] and the Nordic handbook of reinforced soils and fills [7]. However, since 2010, European countries under European standards' jurisdiction must conform to Eurocode 7: geotechnical design [8].

3 METHODOLOGY

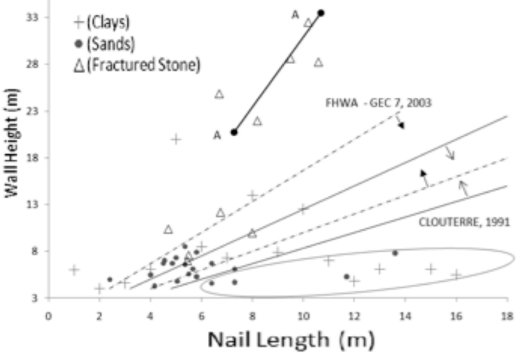
Over the past 20 years soil nailing has moved from proprietary techniques to a standardised approach adoptable on public projects. To what extent this state of the art is actually adopted is the main consideration herein. A database of 127 case studies was compiled from contractor websites, journal papers, and conference proceedings issued by the Deep Foundations Institute [9], the Chinese Institute of Soil Mechanics and Geotechnical Engineering [10], the Construction Industry Research and Information Association [2] the American Society of Civil Engineers [11], the USDOT [12] and Hong Kong's CEDD [13].

4 ANALYSIS AND RESULTS

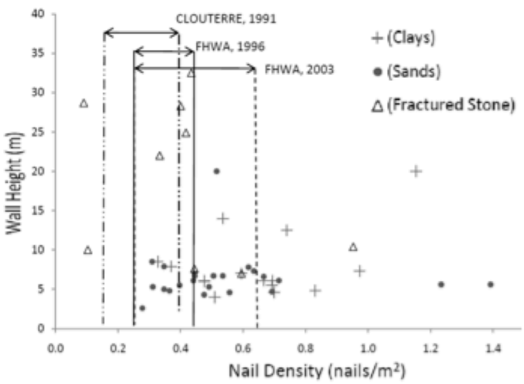
Some results indicate that well-designed and cost-efficient methods are not being followed consistently. Instead, on smaller scale projects (<≈10m), a "rule-of-thumb" approach was commonly applied. Nail densities were calculated using two approaches: dividing the total number of nails by the total area of soil nailing works or multiplying the horizontal by the vertical spacing and then taking the inverse.

4.1 Nail length vs wall height

Design is largely related to the ratio of the nail length (L) to the wall height (H). Values of less than 0.5 were generally not accepted as they do not satisfy sliding or overturning requirements [3]. For bored and grouted soil nails, L/H ratios generally ranged from 0.6 to 1.3 depending on ground conditions, [2] but 0.7-0.85 was most common. Clouterre [1] specified the L/H ratio for bored and grouted nails as 0.8-1.2, which was also adopted by CIRIA [2]. This ratio was modified for U.S. practice to 0.6-1.0 [3.4]. Figure 1 show significant scatter for walls less than 10m high, thereby suggesting less consistent designs than for taller walls; potentially over-designed wall are circled in Fig. 1a. Cases along line A-A are predominantly in fractured stone and above 20m. The increased friction angle of fractured stone allows a reduced L/H ratio for these walls.



a) Nail length vs. wall height



b) Nail density vs. wall height

Figure 1. Nail Installation Characteristics

4.2 Nail Density vs Wall Height

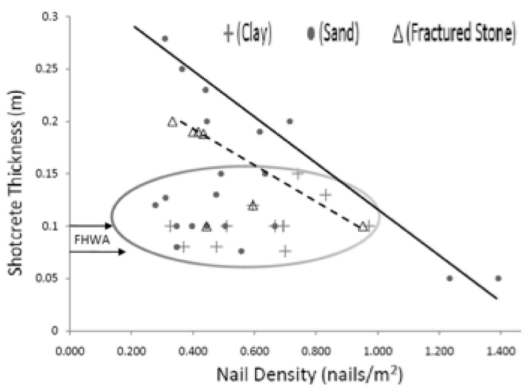
With consideration of nail density versus wall height, the principle that earth pressures are directly related to depth is important. From this, intuition would dictate that the higher a soil nail wall, the larger the earth pressures acting on it would be and therefore, require more soil nails. As can be seen in Fig. 1b, there is no immediately discernible trend in nail density versus wall height. On closer inspection, large walls (> 20m) in fractured stone seem to follow an almost linear relationship between 0.33 and 0.44 nails/m^2, suggesting optimized design. Although a linear trend in nail density would be intuitive, the major de-sign publications refer to acceptable nail spacing, irrespective of wall height. Clouterre [1] lists spacing grids of 2.5-6m^2 for bored and grouted nails, corresponding to nail densities of 0.4-0.16 nails/m^2. The Manual [3] suggests standard grids of 2.25-4m^2 (0.44-0.25 nails/m^2), GEC7 [4] adopts a slightly more conservative approach, specifying grids of 1.56-4m^2 (0.64-0.25 nails/m^2).

CIRIA [2] proposed grid options similar to the other manuals, while Geoguide 7 [5] does not recommend any grid sizes but notes that in Hong Kong, grids of 2.25-4m^2 (0.44-0.25 nails/m^2) are commonly used. Each major, subsequent, design publication has increased both the minimum and maximum nail densities. This increase could be attributed to a growing understanding as to the range of effective densities. Few correlations exist in design manuals relating nail densities and wall heights. This coupled with the explicit proposal of various standard grid dimensions, is likely to continue non-optimized design.

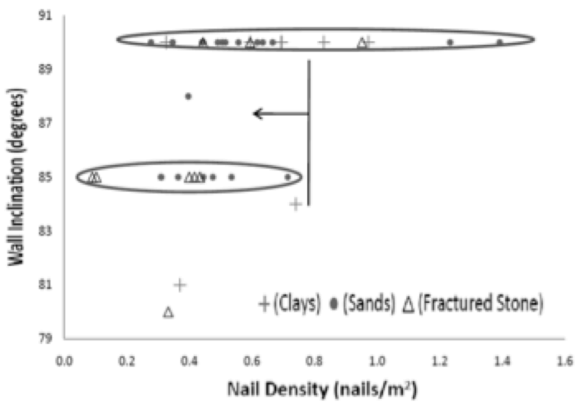
4.3 Nail Density vs. Shotcrete Thickness

When analyzing shotcrete depth versus nail density, an increase in span (the distance between two consecutive nails), generates an increased tributary area, which would suggest a needed increase in shotcrete depth. This relationship would appear as a linear trend in Fig. 2b for many cases in sand and fractured stone. For the majority of cases however, shotcrete depths range 75-150mm (Fig. 2b).

This standardization could be an extension of the FHWA [3,4] recommendations. The earlier Clouterre [1] and later Geoguide 7 [5] recommend calculating shotcrete depth in a project specific manner. Instead, Clouterre [1] suggested standard ranges and ratios for nail density and nail length. Clouterre [1] relates the facing depth to the tensile forces at the nail head. The tensile forces depends primarily on nail spacing (i.e. nail density). Therefore, decreasing shotcrete depths with increasing nail densities would be expected.



a) Nail density vs. shotcrete thickness



b) Nail density vs. wall inclination

Figure 2. Wall characteristics

4.4 *Nail Density vs. Inclination*

Clouterre [1] and GEC 7 [4] discuss the structural benefits of inclining a soil nail wall. The active earth pressure acting on the wall face will decrease, as the wall slope flattens [4], in turn allowing a reduction in nail density/length. Those in sands and clays showed no variation in nail density with inclination, indicating non-optimized design. This contrasts strongly with cases in fractured stone, where a clear 'step down' in nail densities occurs between inclinations of 90° and 85°. When analyzed regardless of soil type a clear drop is evident from nail densities of 0.22-1.4 nails/m^2 for vertical walls to only 0.1-0.575 nails/m^2 for walls inclined 15° from vertical. For a 1000m^2 wall, a 0.1 nails/m^2 reduction would save 100 nails. With a minimum nail length of 2.4m, saving 240m in nail material and related transportation and installation costs. Possible reduction in nail densities by reducing wall inclination is not well documented compared to infor-mation on nail length. Other explanations for not reducing nail densities or for not inclining the wall could be the acceptance of a standard approach or project requirements. A vertical wall is generally chosen for two main reasons [3]: (1) maximize space of a given project and (2) ease of constructability.

5 COST BENEFIT ANALYSIS

The redesign of the soil nail wall, to illustrate the cost implications of non-optimized walls, is presented below. The permanent soil nail wall constructed at Pearsall, Texas in 1995 was originally designed by DP 103 as 4.6m high and 152m long wall to retain an existing highway embankment, in a predominately sandy ground with SPT values of 10-40. The design grout-ground bond was 62kPa was selected for the vertical wall with 1.3m horizontal and 1.1m vertical nail spacing (corresponding to a nail density of 0.7 nails/m^2). The average nail length was 4.7m. Shotcrete for the temporary facing was 76mm; 229mm for permanent.

5.1 *Design Calculations*

The redesign of this project was carried out in accordance with GEC 7 [4].

Step 1: Initial Soil Nail Wall Considerations

1) Wall Layout: Wall height (H), wall length (L_e), and face batter (α) are as follows: H = 4.6 m; Wall Length, $L_e >>$ H; Face batter, α = 10
2) Soil Nail Horizontal and Vertical Spacing, S_H and S_V:
   a) Select Sv = 1.8 m
   b) Select S_H = 1.8 m. $S_H \times S_V = 3.24\ m^2 \leq 4\ m^2$
   c) Values of vertical spacing near top /toe of the wall S_{V0} and S_{VN} = 0.5m
3) Soil Nail Pattern on Wall Face
4) Select Rectangular Pattern
5) Soil Nail Inclination, i:
   a) Select i = 15 for all nails except top row
   b) Select i = 20° degrees for top row
6) Soil Nail Length Distribution: Select a uniform nail length
7) Soil Nail Materials:
   a) Select threaded solid bars
   b) Yield tensile strength, f_y = 520MPa = 0.52 kN/mm^2 (Grade 75)
8) Soil Properties: Φ' = 30 degrees; c' = assumed conservatively as 0; γ = 17 kN/m^3
9) Drillhole Diameter = 0.15m
10) Bond Strength: Design bond strength = 62 kPa
11) Safety Factors:
    a) Nail bar tensile strength factor, F_{st} = 1.8
    b) Facing flexure factor, F_{sff}(temp) = 1.35, F_{sff}(perm) = 1.5
    c) Pullout resistance factor, F_{sp} = 2.0
    d) Global stability factor, F_{sg} = 1.35

Step 2: Preliminary Design

1) Uncorrected Uniform Nail Length:
   a) Design bond strength q_a = 62 kPa
   b) Normalized pullout resistance, μ, $\mu=(q_a D_{DH})/(\gamma S_H S_V)$ = (62×0.15)/ (17×1.8×1.8) = 0.17
   c) Normalized cohesion c*= c'/γH = 0
   d) μ = 0.17 produces a normalized L/H=0.77
   e) Charts used in GEC 7 (FHWA 2003) were developed for: Drill hole diameter = 150mm; Normalized cohesion = 0.02; Global Stability Factor, F_{sg} = 1.35; Drillhole diameter C_{1L} = 0.83; Soil Cohesion C_{2L} = 1.09; Safety Factor C_{3L} = 1.08
   f) Adjusted normalized nail length: $L/H=C_{1L}\times C_{2L}\times C_{3L}\times L/H=0.83\times1.09\times1.08\times0.77=0.75$
   g) The following corrections to L/H are necessary:
      i) To account live load surcharge, increase wall height to 5.2m
      ii) L = 0.75 × 5.2 = 3.9m
      iii) For the needed 3 rows, total nail length, L_{TOT}=3L=3×3.9=11.7m

2) Nail Maximum Tensile Force:
   a) Max design nail force, t_{max-so}, 0.18 from Figure 5.3
   b) Apply Corrections: Drill hole diameter: C_{1F}=1.47; cohesion: C_{2F}=1.09
   c) The corrected normalized maximum nail force is: $t_{max-s}= C_{1F} \times C_{2F} \times t_{max-so} = 1.47 \times 1.09 \times 0.18 = 0.29$
   d) Maximum design nail force: $T_{max-s}=g\times H\times S_V\times S_H\times t_{max-s}=17\times5.2\times1.8^2\times0.29$ =83.06

kN

e) Nail tensile capacity, R_T = Fst × T_{max-s} = 1.8 × 83.06 = 149.5 kN
f) Necessary nail bar cross-sectional area, $A_T=(T_{max-s} \times Fst)/f_y = R_T/f_y$ = 145.5/0.52=288mm^2
g) Area of 25mm diameter threaded bar = 510 mm^2

3) Facing Design:
   a) Design the nail head tensile force: $T_o = T_{max-s}$ [0.6 + 0.2(S_V – 1)] = 83.06[0.6+0.2(1.8 – 1)] = 63.13 kN
   b) Temporary Facing: Shotcrete thickness (h) = 76 mm; f'_c (compressive strength) = 21MPa; and Welded wire mesh reinforcement, f'_y = 420 MPa
   c) Permanent Facing: CIP concrete thickness (h) = 100mm; d = 50mm; f'_c = 21MPa; f'_y = 420MPa
      i) Limiting reinforcement ratios, r_{min} (%) = = 0.175; r_{max}(%) = = 1.09
      ii) Considering the width of the analysis section as 1 m, a_s = rd; $a_{s\ min}$ = 66.5 mm^2/m; $a_{s\ max}$ = 414 mm^2/m
      iii) Select reinforcement; use a mesh 300 × 300 of (12 mm bars) – Area per unit length at midspan a_{sm} = 377 mm^2/m
      iv) Reinforcement ratios along each section and the total reinforcement ratio are: $r_{hm} = r_{hn} = r_{vm} = r_{vn}$ = ((377)/(1000×100))×100 = 0.38% r_{tot} = .76 %
      v) Select Factor C_f= 1, Table 2 R_{FF} = × (377+ 377) (mm^2/m) × 0.1 (m) × 420 (Mpa) = 123 kN
      vi) Ultimate loads (kN) $FS_{FF} \times T_o$, FS_{FF} = 1.5 for Permanent Facings 1.5 × 63.13 = 94.7 ≤ 123 kN
   d) Punching Shear Resistance (R_{FP}) for temporary facing: Calculate R_{FP} for temporary facing: The punching shear failure consists of the failure of a truncated cone of mean diameter $D'_c = L_p$+ h, where L_p is the bearing plate length. The resisting shear force on this cone, V_f, is V_F =330× ×π ×D'_c(m)×h(m); V_F=330××π×(0.225+0.1)×0.1= 154

   Resistance against punching shear failure is: $R_{FP} = C_pV_F$ where C_p =1

   R_{FP} = 154.4 ≥ 85 kN – (FS × T_o), (1.35 × 63.13)
   e) Punching Shear Resistance (R_{FP}) for permanent facing: D'_c is defined for permanent facing as D'_c = minimum of S_{HS} +h_c or 2h_c where S_{HS} is the headed-stud separation and h_c the effective headed-stud length (Table 3).

   h_c = Ls + t_p – t_{SH} = 105+25–7.9 = 122.1

   where, Ls, t_p and t_{SH} are the stud length, plate thickness and stud thickness, respectively D'_c = min (150 + 122.1 or 2×122.1) = 244; V_F=330× ×π ×D'_c(m)×h(m); V_F=330××π×(0.244)×0.122= 141.4

   Resistance against punching shear failure is: $R_{FP} = C_pV_F$, where C_p =1

   R_{FP}=141.4≥94.7kN–(FS×T_o), (1.5× 63)
   f) Headed-Stud tensile resistance (R_{FS}): Nail headed-stud tensile capacity: R_{FS}= 4A_H×f_y = 4 × ((π × d^2)/4) × .420 = 213 kN ≥ 126 kN–(FS×T_o), (2×63.13) where A_H is the headed-stud area.

This resulted in the data shown in Table 1, which meets all of the design criteria and the redesign shown in Table 2.

Table 1. Bearing plates and headed studs (from [4])

Bearing plate	Type	4 headed-studs 0.5 x 4.125
	Steel	250 MPa (Grade 420)
	Dimensions	Length; L_p = 225 mm and Thickness t_p = 25mm
Headed studs	Dimensions	Nominal length; L_n=105mm; head diameter; D_h= 25.4mm; shaft diameter; D_s=12.7mm; head thickness t_H =7.9mm; spacing; S_{SH} =150mm

Table 2. Design and Redesign Parameters

Parameter	Original Design	Redesign
Inclination	90°	80°
Nail spacing grid	1.3m h x 1.1m v (1.43m^2)	1.8 x 1.8m (3.24m^2)
Permanent facing depth	229mm	100mm

5.2 Cost Savings

Using a cost of $125/m^3 for concrete and 12.25/m for reinforcing, total cost savings totaled $22,006 (Table 3) represents a 7.2% cost reduction. These figures do not include the potential savings in drilling, grouting and labour, associated with smaller nail lengths and facing depths. The estimated cost was $393/m^2 of soil nail wall × 539m^2 of wall = $211,827 in 1995. Using an inflation factor of 1.447 [14], the total 2011 cost was $306,513 USD.

Table 3. Cost savings from redesign

	Actual design	Re-design	Savings	Costs ($USD)	Savings ($USD) = (savings x costs)
Nails (m)	2,199.6 m	994.5 m	1,205.1 m	12.67/m	15,268.62
Shotcrete	76 mm	76 mm	NA	NA	NA
Concrete	123.4 m^3	69.5 m^3	53.9 m^3	125/m^3	6,737.5
				Total Savings	22,006

6 CONCLUSIONS

This paper examined data from over 100 case studies, and uncovered potential trends related to non-optimal design of soil nailing projects. These designs appear to be due to a tendency to build as a standard instead of to a standard. This default approach to design may be due to the proprietary nature in which the technology evolved with a lack of harmonization across design manuals. The ratios of length to height decreased with every major research report published. This change shows a progression in design practices with increased knowledge and/or confidence. The redesign of a relatively small project (539m^2) saved $22,000 (7.2%) on just materials.

ACKNOWLEDGMENTS

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